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Search for Doubly Charged Higgs Bosons at LEP2

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Abstract

A search for pair-produced doubly charged Higgs bosons has been performed using the data collected by the DELPHI detector at LEP at centre-of-mass energies between 189 and 209 GeV. No excess is observed in the data with respect to the Standard Model background. A lower limit for the mass of 99.1 GeV/c^2 at the 95% confidence level has been set for doubly charged Higgs bosons in left-right symmetric models.

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1 Introduction

Doubly charged Higgs bosons ($H^{\pm\pm}$) appear in several extensions to the Standard Model [1], such as left-right symmetric models, and can be relatively light. In Supersymmetric left-right models usually the $SU(2)_R$ gauge symmetry is broken by two triplet Higgs fields, so-called left and right handed. Pair-production of doubly charged Higgs bosons is expected to occur mainly via s-channel exchange of a photon or a Z boson. In left-right symmetric models the cross-section of $e^+e^- \to H_L^{++}H_L^{--}$ is different from that for $e^+e^- \to H_R^{++}H_R^{--}$, where $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ are the left-handed and right-handed Higgs bosons. The formulae for the decays and the production of these particles can be found in [2].

In these models the doubly charged Higgs couples only to charged lepton pairs, other Higgs bosons, and gauge bosons, at the tree level. The current limit and the mass range of this analysis is restricted to the interval between 45 GeV/c^2, the LEP1 limit set by OPAL [3], and the kinematic limit at LEP2, that is around 100 GeV/c^2. The dominant decay mode of the doubly charged Higgs boson is expected to be a same sign charged lepton pair, the decay proceeding via a lepton number violating coupling. As discussed in [2], due to limits that exist for the couplings of $H^{\pm\pm} \to e^\pm e^\pm$ from high energy Bhabha scattering, $H^{\pm\pm} \to \mu^\pm\mu^\pm$ from the absence of muonium to anti-muonium transitions and $H^{\pm\pm} \to \mu^\pm e^\pm$ from limits on the flavour changing decay $\mu^\pm \to e^\mp e^\pm e^\pm$, electron and muon decays are not likely. In addition, most of the models expect that the coupling to $\tau\tau$ will be much larger than any of the others. Therefore, only the doubly charged Higgs boson decay $H^{\pm\pm} \to \tau^\pm\tau^\pm$ is considered here.

The partial width for the $H^{\pm\pm}$ decay into two τ leptons is, at the tree level [2]:

$$\Gamma_{\tau\tau}(H^{\pm\pm} \to \tau^\pm\tau^\pm) = \frac{h_{\tau\tau}^2}{8\pi} m_H (1 - \frac{2m_\tau^2}{m_H^2})(1 - \frac{4m_\tau^2}{m_H^2})^{1/2} \tag{1}$$

where m_τ is the mass of the τ lepton and $h_{\tau\tau}$ is the unknown $H\tau\tau$ Yukawa coupling constant. In this analysis, we assume that $h_{\tau\tau}$ is sufficiently large ($h_{\tau\tau} \geq 10^{-7}$) to neglect the decay length of the Higgs boson.

Searches in this channel have already been performed at LEP2 by the OPAL experiment [4].

2 Data Analysis

The data collected by DELPHI during the LEP runs at centre-of-mass energies from 189 GeV to 209 GeV were used. The total integrated luminosity of these data samples is $\sim$ 570 pb^{-1}. The DELPHI detector and its performance have already been described in detail elsewhere [5, 6].

Signal samples were simulated using the PYTHIA generator [7]. In this analysis samples with doubly charged Higgs boson with masses between 50 and 100 GeV/c^2, in 10 GeV/c^2 steps, were used at different centre-of-mass energies, both for left-handed and right-handed bosons.

The background estimates from the different Standard Model processes were based on the following event generators, interfaced with the full DELPHI simulation program [6]: the WPHACT [8] generator was used to produce four-fermion events Monte Carlo simulation. The four-fermion samples were complemented with dedicated two-photon collision samples generated with BDK, BDKRC [9] and PYTHIA [7]. Samples of $q\bar{q}(\gamma)$ and $\mu^+\mu^-(\gamma)$ events were simulated with the KK2f generator [10]. Finally, KORALZ [11] was used to simulate $\tau^+\tau^-(\gamma)$ events and the generator BHWIDE [12] was used for $e^+e^-(\gamma)$ events.

3 Selection

The final state resulting from $e^+e^- \to H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$ consists of four narrow and low multiplicity jets coming from the τ decays. An initial set of cuts was applied to select events with four jets of low multiplicity. A charged particle multiplicity between 4 and 8 was required. Events were clustered into jets, requiring each jet to be separated from the others by at least 15 degrees, and only events with four reconstructed jets were accepted. To improve the reconstruction of the tau energy, the tau momenta were rescaled, imposing energy and momentum conservation and keeping the tau directions at their measured values. If any jet momentum was negative, the event was rejected, as they are commonly not genuine four-jet events.

The two-photon background was reduced by the following energy and momentum requirements: the visible energy outside a cone of 25° around the beam had to be greater than $0.15\sqrt{s}$, the momenta of the jets were required to be larger than $0.01\sqrt{s}$ and the total neutral energy had to be less than $0.35\sqrt{s}$.

The four lepton background was rejected by requiring that the momentum of the most energetic lepton identified (electron or muon) was less than $0.25\sqrt{s}$ and the momentum of the second most energetic lepton identified was less than $0.15\sqrt{s}$. Algorithms used in the lepton identification were the same as those used in the selection of fully-leptonic W pairs [13].

The calculated tau momenta, defined above, were used to reconstruct the Higgs mass. The charge of the tau jet was calculated as the sum of the charges of the charged particles. If this value was not ± 1, then the charge of the most energetic charged particle was assumed as to be the charge of the tau jet. For events with two positive τ lepton candidates and two negative τ lepton candidates the charge was used to assign the pairing of both doubly charged Higgs bosons. If the total charge was not equal to 0, the pairing was chosen to minimise the difference between the two reconstructed masses of the Higgs bosons. The ratio $\frac{|M_{H^{++}} - M_{H^{--}}|}{0.5 \cdot (M_{H^{++}} + M_{H^{--}})}$ was required to be less than 0.7. Finally the reconstructed event mass, defined as the average of the mass of the two pairings, had to be greater than 40 GeV/c^2. The reconstructed event mass was used as an additional discriminant variable in the computation of the confidence levels.

The effects of the selection cuts are shown in Table 1 for the combined 189-209 GeV sample. After all cuts were applied only one event was observed in the data with a mass of 69$\pm$3 GeV/c^2, while 0.9 events were expected from background processes. The candidate was collected at $\sqrt{s}$=206.7 GeV and is compatible with the assignment $ZZ \to \tau^+\tau^-\tau^+\tau^-$. The most probable reconstructed masses with different sign leptons are indeed compatible with a 90-90 GeV/c^2 mass hypothesis at the one sigma level. The signal efficiency was around 40% for a wide range of masses between 70 and 100 GeV/c^2 for both left-handed and right-handed doubly charged Higgs, as shown in Table 2. The final reconstructed mass plot and the expected mass distribution in simulated signal events are shown in

Figure 1. The good level of agreement between data and simulation observed at different stages of the analysis is demonstrated in Figure 2.

cut	data	total bkg.	$llll$	other	$\varepsilon_{H_L^{++}H_L^{--}}$
Four jets preselection	60	67.4	44.0	23.4	59.2%
anti $\gamma\gamma$ cuts	26	31.0	28.9	2.1	52.3%
anti 4 lepton cuts	1	1.9	1.7	0.2	48.7%
Mass requirements	1	0.9	0.8	0.1	44.2%

Table 1: The total number of events observed and the expected background after the different cuts used in the analysis for the combined 189-209 GeV sample. The last column shows the efficiency for a left-handed doubly charged Higgs boson signal with $m_{\mathrm{H}_L^{\pm\pm}} = 100$ GeV/c^2 at $\sqrt{s}$=206.7 GeV.

channel	$M_{H^{\pm\pm}}$ (GeV/c^2)					
	50	60	70	80	90	100
left-handed	32.7	36.6	40.5	44.8	43.4	44.2
right-handed	31.8	37.0	40.0	44.0	44.8	45.2

Table 2: Selection efficiencies (in %) for left-handed and right-handed $H^{++}H^{--} \rightarrow \tau^+\tau^+\tau^-\tau^-$ for several $H^{\pm\pm}$ masses at $\sqrt{s}$=206.7 GeV. The statistical error is around 1.5% in all cases.

4 Systematic uncertainties

Several sources of systematic uncertainties were investigated for their effect on the signal efficiency and the background level. The particle identification was checked on di-lepton samples both at the Z peak and at high energy. The discrepancy on the efficiencies between the data and the simulation were found to be lower than 2% in all cases. The track selection and the track reconstruction efficiency was also studied with these samples. These effects were studied by the comparison between data and simulation at the boundaries of sub-detectors. The systematic error of these effects was about 1.5%.

The errors on the background and signal rates from the modelling of the preselection variables and the detector response were a few percent. Different variables at preselection level have been studied, with good agreement between data and simulation observed. The distributions in relevant variables before the anti $\gamma\gamma$ cuts and the anti four lepton cuts are shown in Figure 2. The masses reconstructed from both same sign and different sign lepton pairs, before the anti four lepton cuts were applied, are shown in Figure 3. For the opposite sign lepton pairs only the mass of the combination closest to the Z mass has been given and the Z peak is clearly visible.

The dominant part of the background uncertainty ($\sim$ 12%) is due to the limited simulation statistics available. The total systematic error on the background is about 13%. The total systematic error on the efficiency is about 5%.

5 Determination of the mass limit

No evidence for $H^{++}H^{--}$ production was observed. A likelihood ratio technique [14] has been used to compute the cross-section and mass limits. The reconstructed event mass was used as discriminant variable in the computation of the confidence levels. All centre-of-mass energies was treated as separate experiments in the likelihood function.

A very similar behaviour, both in terms of efficiency and of mass distributions, was observed for the left-handed and the right-handed doubly charged Higgs bosons. Hence, the average of both contributions were used to calculate the confidence levels. The expected left-handed and right-handed cross-sections were calculated using the PYTHIA generator [7].

Previous searches for $H^{\pm\pm}$ pair production have already excluded $M_{H^{\pm\pm}} < 45.6$ GeV/c^2 [3]. Therefore, we have limited this search to masses greater than this value.

Figure 4 shows the 95% confidence level upper limit on the cross-section at $\sqrt{s} = 206.7$ GeV for the production of $H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$. The comparison of this limit with the expected cross-section for left-handed $H_L^{\pm\pm}$ and right-handed $H_R^{\pm\pm}$ pair production yields 95% confidence level lower limits on the mass of the $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ bosons of 99.6 and 99.1 GeV/c^2 respectively.

6 Conclusion

A search for pair-produced doubly charged Higgs bosons was performed using the data collected by DELPHI at LEP at centre-of-mass energies from 189 GeV to 209 GeV in R-parity conserving supersymmetric left-right symmetric models. No significant excess was observed and a lower limit on the doubly charged Higgs mass of 99.1 GeV/c^2 is set at 95% confidence level.

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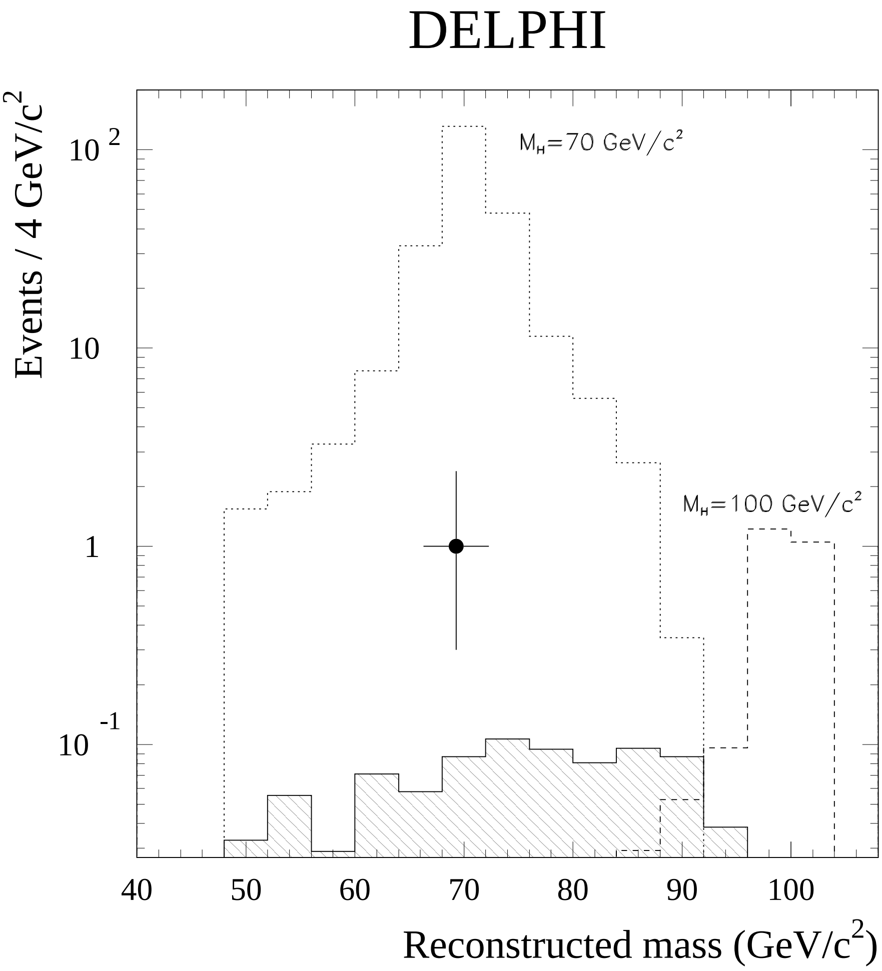

Figure 1: The reconstructed mass distribution after all cuts. The hatched histogram corresponds to the expected background and the dot with the error bar shows the one remaining candidate event. The dashed line corresponds to $m_{\mathrm{H}_L^{\pm\pm}} = 70$ GeV$/c^2$ and the dotted line corresponds to $m_{\mathrm{H}_L^{\pm\pm}} = 100$ GeV$/c^2$.

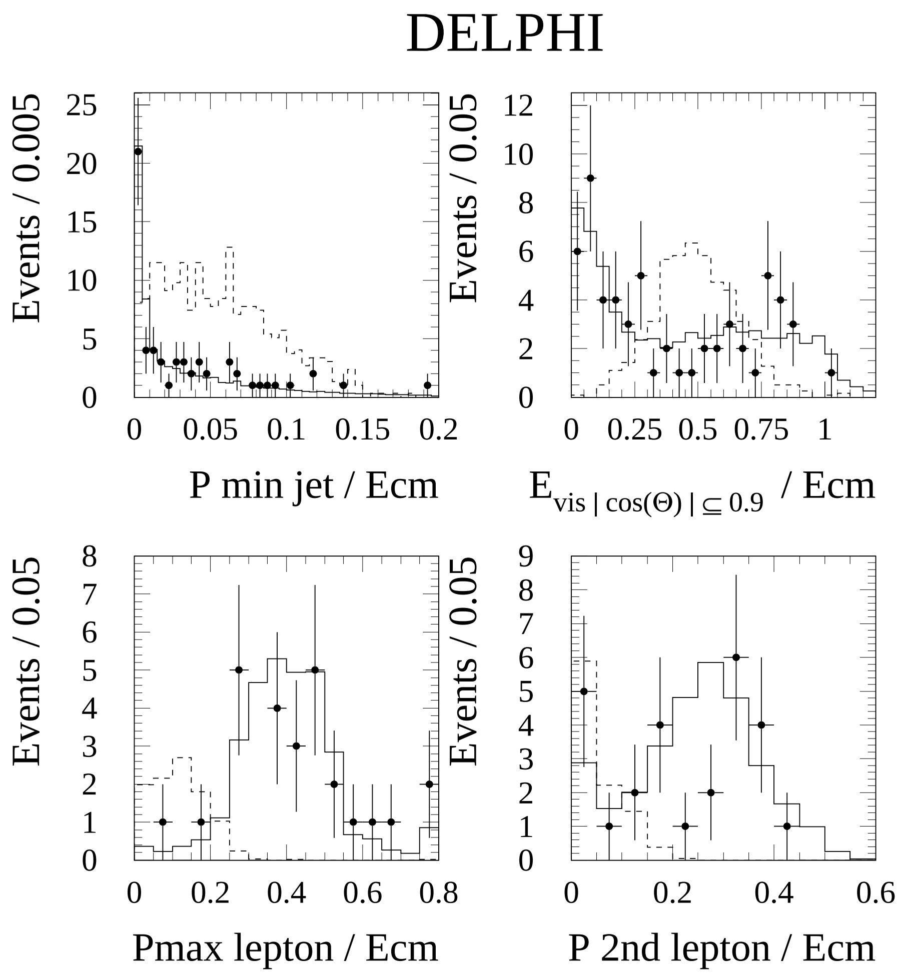

Figure 2: Event selection variable distributions at different stages of the analysis. The top plots show the minimum momentum of the jets and the visible energy outside 25° around the beam pipe scaled by $\sqrt{s}$ after the four jet preselection cuts. The bottom plots show the momentum of the most energetic identified lepton and the momentum of the second most energetic identified lepton scaled by $\sqrt{s}$ after the anti $\gamma\gamma$ cuts. The solid lines show the expected background, the dots the observed data and the dashed lines correspond to $m_{\mathrm{H}_L^{\pm\pm}} = 100$ GeV/c^2 in arbitrary units.

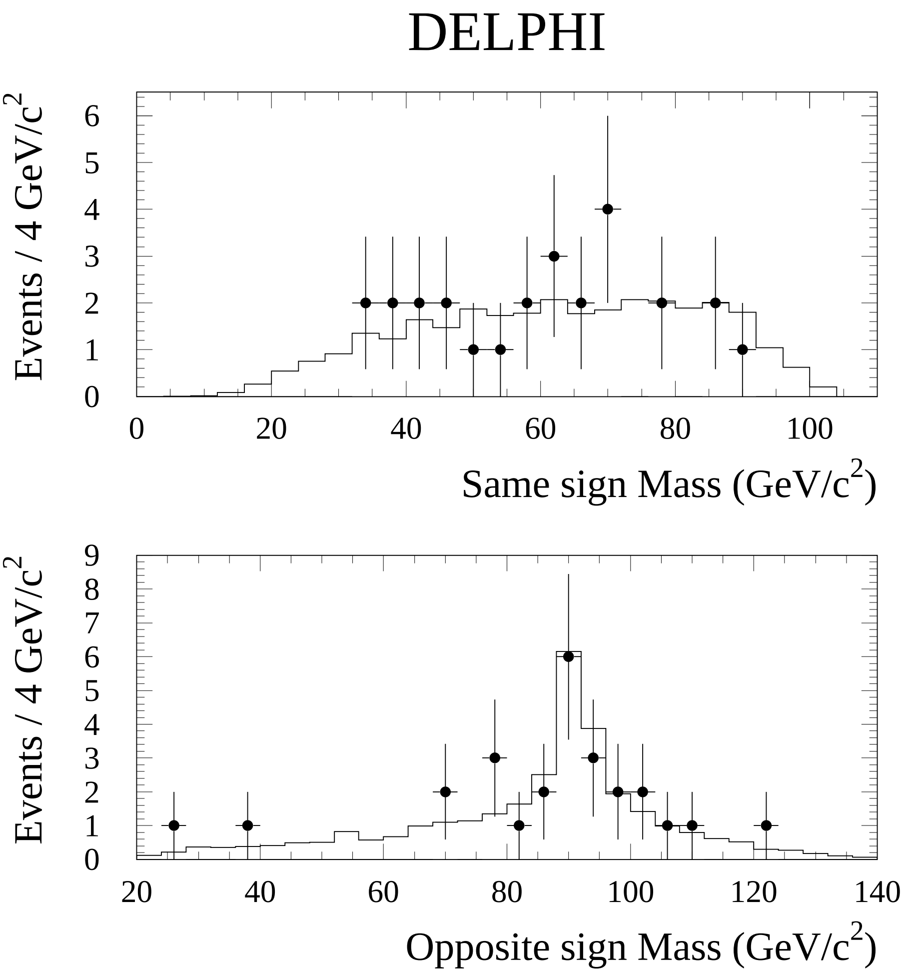

Figure 3: Reconstructed mass with same sign lepton pairs (top) and opposite sign lepton combination nearest to the Z mass (bottom). These distributions are shown before the anti four lepton cuts.

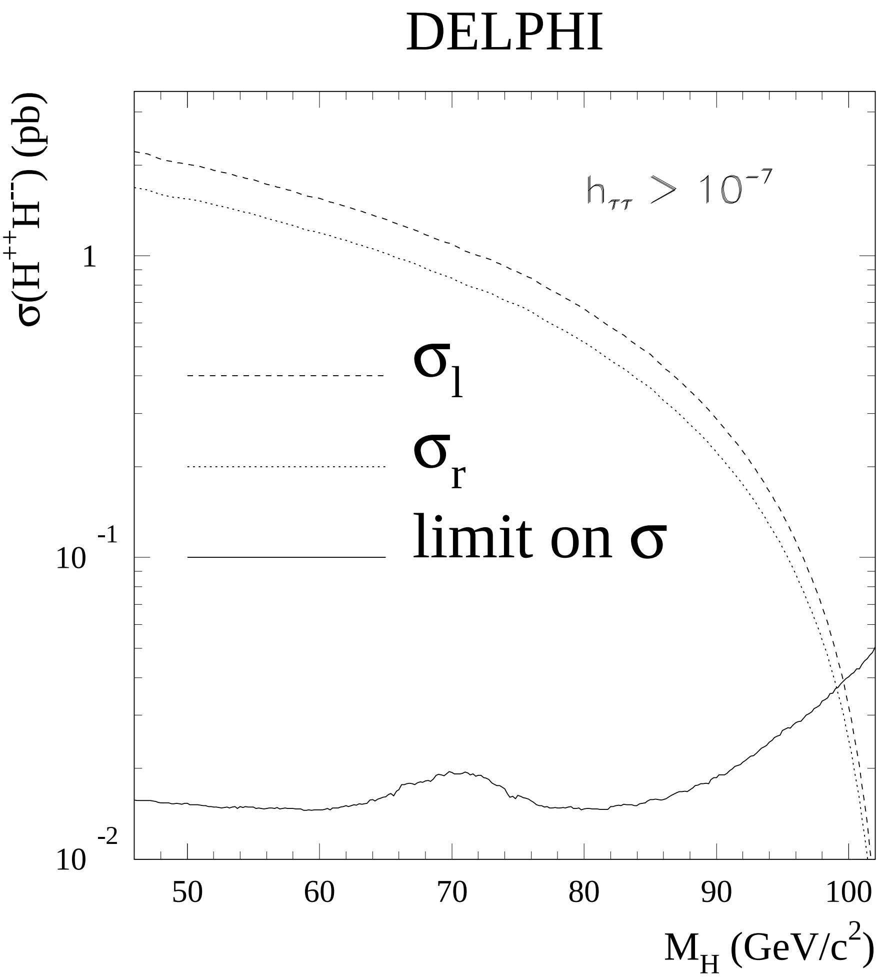

Figure 4: The solid line shows the 95% confidence level upper limit on the $H^{\pm\pm}$ pair production cross-section at $\sqrt{s}$=206.7 GeV assuming 100% branching ratio for the decay of $H^{\pm\pm}$ into $\tau^{\pm}\tau^{\pm}$. The dashed and dotted lines show the expected production cross-section of $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ pairs in left-right symmetric models.